

IAC-18-A3.3A.4

The Mars Reconnaissance Orbiter Mission: 2018 Status

**M. Daniel Johnston^{1*}, Martin.D.Johnston@jpl.nasa.gov;
 Richard W. Zurek¹, Richard.W.Zurek@jpl.nasa.gov**

¹ Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, 91109, USA

* Corresponding Author

Abstract

The Mars Reconnaissance Orbiter (MRO) continues its dual-mode mission of scientific exploration and programmatic support. Now in its 13th year of flight (and its 12th year in its low-altitude, sun-synchronous orbit around Mars), the spacecraft continues in its normal flight mode and its science instruments continue to acquire a treasure trove of data which is being used to study the Martian environment (surface, sub-surface, and atmosphere). To date (July 2018), more than 333 TB of scientific data have been returned to Earth. Building onto the 2017 IAC paper: “The Mars Reconnaissance Orbiter Mission: Continuing a Record of Exploration from Mars Orbit,” [1] this paper provides a 2018 status update on the MRO Mission. A signature event since the 2017 writing is the onset and evolution of a planet-encircling dust event (PEDE), the first such event since 2007. Additional recent science highlights for MRO include the discovery of mid-latitude ice cliffs, polar cap characterization, daily global mapping of the 2018 PEDE dust activity and the atmospheric thermal response, further characterization of the tantalizing recurring slope lineae (RSL), and continued detection of surface changes. Programmatically, UHF relay support for the Mars Science Laboratory (MSL) rover *Curiosity* and the Mars Exploration Rover (MER) rover *Opportunity* continues at a pace that provides the engineers and scientists operating those surface vehicles timely information to support their mission planning and science analysis. Most of the landing site characterization requests for the NASA Mars 2020 rover and the ESA ExoMars Rover/Surface Platform (RSP) missions have been completed, with final acquisitions delayed due to the obscuring dust haze from the current PEDE. In parallel, the flight team has faced new engineering challenges as the spacecraft has aged. The team has developed and is implementing actions that are aimed at stretching spacecraft battery life. A new all-stellar capability using the spacecraft’s star trackers now allows for normal spacecraft operations without IMUs. In addition to its current relay duties, MRO will be synchronized to provide critical communications support for the *InSight* Entry, Descent, and Landing (EDL) event on November 26, 2018, and will be readied to support *InSight*’s critical commissioning phase with UHF relay support and environmental characterization. A new split-pass relay capability has been developed which will allow *MRO* to relay with two surface vehicles in “close proximity” on the same overflight, i.e. the *InSight* lander and the *Curiosity* rover. Extended for another year of operations by NASA, this paper will highlight recent scientific progress and describe actions that will extend *MRO*’s life well into the 2020’s as a key element of the Mars Exploration Program.

Keywords: Mars Reconnaissance Orbiter, Mars Exploration, Mars

Acronyms

ADR	Adaptive Data Rates	JPL	Jet Propulsion Laboratory
AS	All-Stellar	LIM	Laser Intensity Monitor
C&DH	Command & Data Handling	LMST	Local Mean Solar Time
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars	LTST	Local True Solar Time
CTX	Context Imager	MARCI	Mars Color Imager
DSN	Deep Space Network	MCS	Mars Climate Sounder
EDL	Entry, Descent, & Landing	MEP	Mars Exploration Program
EDM	EDL Demonstration Module	MER	Mars Exploration Rover
EM	Extended Mission	MGS	Mars Global Surveyor
EMI	Electromagnetic Interference	MRO	Mars Reconnaissance Orbiter
EOD	End of Discharge	MSL	Mars Science Laboratory
ESA	European Space Agency	NASA	National Aeronautics & Space Administration
EZ	Exploration Zone	OTM	Orbital Trim Maneuver
HiRISE	High Resolution Imaging Science Experiment	PEDE	Planet-Encircling Dust Event
IMU	Inertial Measurement Unit	RQM	Relay Quiet Mode
		RSL	Recurring Slope Lineae
		SHARAD	Shallow Subsurface Radar

SNR	Signal-to-Noise
WAC	MGS Wide Angle Camera
Tb	Terabits
TES	Thermal Emission Spectrometer
UHF	Ultra High Frequency

1. Introduction

The Mars Reconnaissance Orbiter (MRO) Project is a major element of the Mars Exploration Program (MEP). The MRO spacecraft was launched on August 12, 2005, entered Mars orbit on March 10, 2006, and after 6 months of aerobraking, was established in its low-altitude, solar fixed (~3 am–pm) near-circular polar orbit (~255–320 km) [2]. In June 2018 MRO was approved for a one-year mission extension by NASA guided by the same scientific and programmatic goals as its current Extended Mission 4 (EM4). This extension -- known as EM4 Extended (EM4E) -- will span the time period from October 2018 through September 2019 and will continue observations of the Martian surface, subsurface, and atmosphere as well as telecommunications relay for landed missions.

1.1 Extended Mission Objectives

MRO is a dual-mode mission having both scientific and programmatic support objectives [3]. The four major scientific goals of EM4E are focused on a “Mars in Transition” theme. Those scientific goals are to:

- Understand Environmental Transitions and Habitability of Ancient Mars;
- Understand Ices, Volcanism, and Climate of Amazonian Mars;
- Understand Surface Changes and its Implications for a Modern Dynamic Mars; and
- Understand Atmospheric and Polar Processes of a Modern Dynamic Mars.

In addition to its scientific objectives, MRO will continue its mission support to active and future missions. The primary programmatic support objectives include:

- UHF surface relay link for landed vehicles;
- Recording of critical event telemetry for entry, descent, and landing (EDL) vehicles;
- Landing site reconnaissance;
- Support of mission surface operations; and the
- Delivery of environmental data to support mission design and EDL planning.

1.2 Spacecraft/Payload Description

The MRO spacecraft, shown in Figure 1, is a very capable remote sensing science platform. It has seven

science investigations supported by six science instruments, and it carries a UHF telecommunications radio (Electra) for surface relay. The spacecraft was developed to support atmospheric limb, on planet and regional surface and subsurface survey from a near-circular, low altitude orbit (~280-315 km). A key capability of the vehicle is its ability to routinely carry out targeted, high-resolution surface observations. The spacecraft is 3-axis stabilized with large momentum wheels providing stability and control. In order to reduce pointing errors resulting from navigation uncertainties, the orbiter uses an on-board ephemeris-driven pointing algorithm that allows for precise surface targeting. To return large volumes of scientific data to Earth, the spacecraft has a powerful telecommunications and command & data handling (C&DH) architecture that communicates up to 16 hours a day with the Deep Space Network (DSN).

The science payload for the mission consists of [4]: a high-resolution imager (capable of resolving 1-meter-scale objects with 30 cm per pixel from 300km altitude) [HiRISE – High Resolution Imaging Science Experiment]; a visible/near infrared imaging spectrometer [CRISM – Compact Reconnaissance Imaging Spectrometer for Mars]; an atmospheric sounder [MCS – Mars Climate Sounder]; a subsurface radar sounder [SHARAD – Shallow (Subsurface) Radar], a weather camera [MARCI – Mars Color Imager]; and a context optical imager [CTX – Context Imager] to provide lower-resolution but wider field-of-view. In addition to the science payloads, spacecraft radiometric data are used to support gravity science studies.



Figure 1. Artist rendering of the MRO Spacecraft

1.3 Spacecraft Operability and Target Planning

The MRO spacecraft is normally oriented such that its payload elements remain nadir-pointed to Mars.

Owing to its gimballed high gain antenna (HGA), the spacecraft can simultaneously acquire science and relay data and return that data to Earth nearly continuously over an orbit (except for periods of Mars occultation or for gaps in DSN coverage). Additionally, the MRO spacecraft can usually cross-track roll up to $\pm 30^\circ$ from nadir to enhance its targeting field-of-view, to produce stereo from separate view angles, or for higher signal-to-noise radar observations. Gimballed solar arrays allow the spacecraft to maintain power by sun tracking even while rolling. Science surface targets and relay support passes are scheduled and acquired using an onboard flight software targeting module. Surface target accuracy is maintained by performing navigation ephemeris updates to the spacecraft twice a week.

The MRO orbit and thus ground track walk were chosen so that practically any place on Mars can be seen ≥ 2 times in any 17-day period, using off-nadir rolls. This means that repeat views of the same locale (as needed for stereo or for landing site coverage) can be achieved in a few weeks. Restriction to nadir viewing would increase that time to more than 100 days for low latitude sites

(where most candidate landing site ellipses are). With an 112-minute orbit period, MRO completes 12-13 orbits each day.

1.4 MRO Extended Mission Timeline

The overall mission timeline for EM4E is shown in Figure 2. It includes Mars seasons; global dust storm periods; the 2019 solar conjunction command moratorium period; spacecraft constraints on flight activities such spacecraft roll limits; predicted daily data volume estimates; local mean solar time (LMST) drift and associated local true solar time (LTST). Such LMST drifts are generally to ensure coverage of other mission critical events. It also includes significant events from other missions: InSight launch, cruise, and EDL; ongoing MSL and MER-B surface operations. During EM4E, MRO will continue to be maintained in its nominal low altitude science orbit.

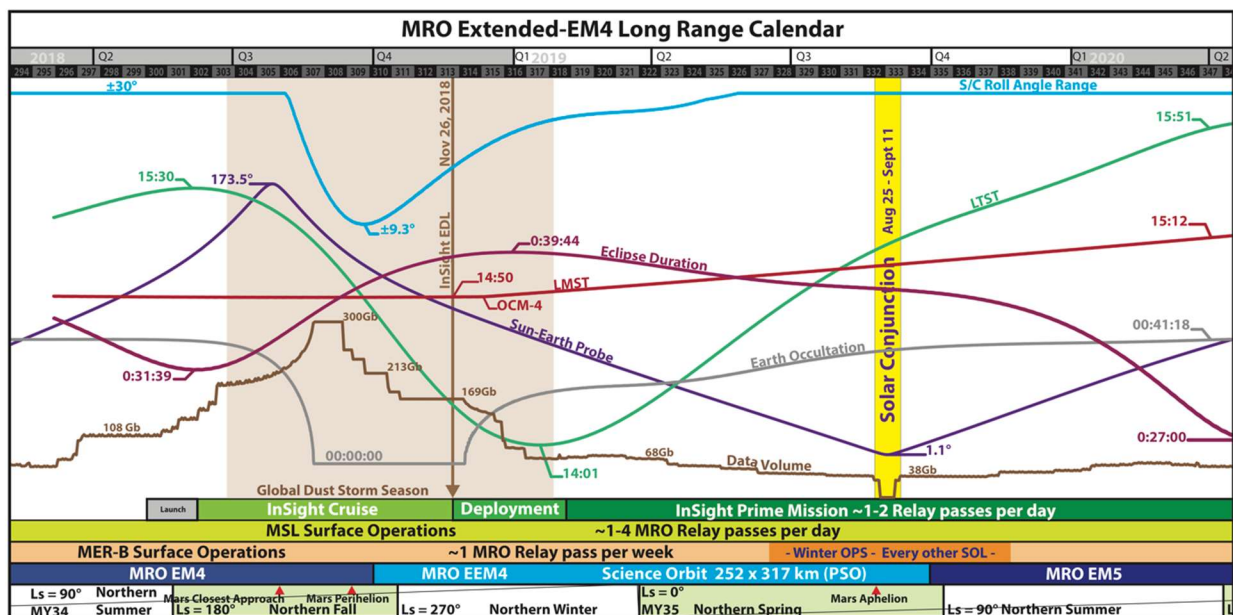


Figure 2. MRO EM4 Extended Timeline (October 2018 – September 2019)
 [Timeline spans the period from February 2018 to April 2020]

Curves show spacecraft roll limits (blue), LMST drift (red), associated LTST (green), Sun-Earth-MRO angle (purple), and projected volume of data returned (brown). Solar conjunction is also marked (vertical yellow bar). The southern spring-summer great dust storm season is shown (brown shading); a planet-encircling dust storm occurred at its start.

2. Selected Science Results

A key emphasis of MRO during its 4th Extended Mission (EM4) was to further understand change on the planet, early in its history, in recent geologic times and occurring even today. Indications of such change were detected in the 3rd Extended Mission and earlier mission phases and are now being investigated more systematically. Of course, Mars has been “in transition” since its earliest days [5] and change continues even today. The following highlights are organized around the goals of EM4/EM4E.

2.1 Transitions in Ancient Environments

Evolution of the igneous rock composition since the end of the Noachian period has been difficult to ascertain because of the more recent dust cover of the ancient crust. MRO CRISM addressed this by systematic imaging of fresh craters over many years. At over 50 locations (Fig. 3), the mafic bedrock was exposed and CRISM detected mineralogy similar to two previously recognized Noachian compositions first identified by the OMEGA instrument on Mars Express. These similar mafic mineralogies indicate that the rock composition was little altered since its early formation, suggesting that warm, liquid water was not prevalent after the late Noachian. This does not rule out episodic activity, especially if sourced by snowmelt (i.e., cold temperatures).

With the inability of CRISM's last working cooler to produce cold temperatures, the IR spectrometer is no longer able to return data with adequate signal-to-noise. However, the visible spectrometer continues to operate nominally and its data can still spectrally trace certain aqueous minerals, such as the Jarosite deposits shown in Figure 4. With CRISM IR data collection at an end, the investigation team is focusing on reprocessing the IR data into improved map-tile mosaics and on collecting VNIR data, including a global survey map at 100 m/pixel resolution.

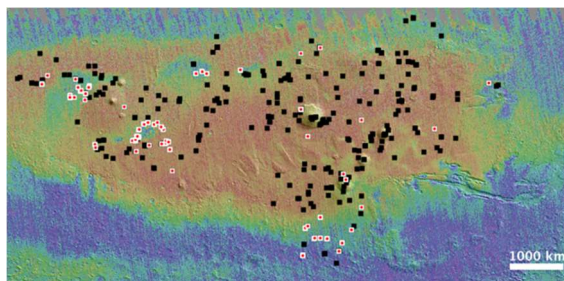


Figure 3. MRO CRISM examined mineralogy of Amazonian-age bedrock exposed in fresh impact craters to characterize environmental transitions [6].

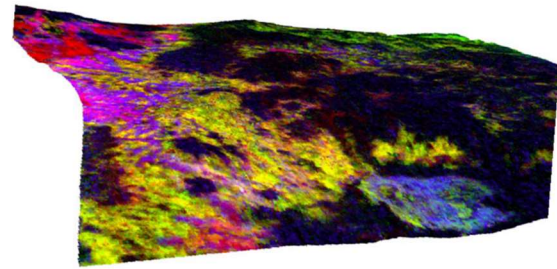


Figure 4. Fe/Mg smectite (red), sulfates and Al-clays (pink-yellow), jarosite (green), jarosite/phylosilicates mixtures (blue). Minerals such as these resemble "salt ponds" as found in SW Australia or the Antarctic Dry Valleys.
 (MRO CRISM / JHUAPL / JPL / NASA)

2.2 Mid-Latitude Ice and Ice Ages

MRO SHARAD has revealed buried ices of water and carbon dioxide [7-8], evidence of geologically recent climate change. Continuing work exploring the three-dimensional structure of the polar caps [9-10] has revealed apparent impact craters at the base of the north polar permanent cap (Figure 5), consistent with a Hesperian age for the basal unit underlying the younger ice cap. Mapping of the south polar deposits indicates a CO₂ subsurface ice volume of ~16,500 km³, 11% larger than previous estimates [11]. The known distribution of very shallow ice (within 1-2 meters of the surface) continues to be extended by viewing new impact craters with bright, white floors, revealing nearly pure ice [12]. Radar has indicated more extensive subsurface ice deposits at mid-to-high latitudes [13-14], although some uncertainty as to the degree of ice content remains [15]. Such ice might one day provide resources to humans exploring on the surface of Mars.

2.3 Surface Changes on Modern Mars

The combination of a long mission and very-high-resolution imaging has enabled MRO to detect several categories of surface change. One of the most tantalizing discoveries of the mission has been the Recurring Slope Lineae (RSL) which are narrow linear strips of ground that darken on steep slopes during the warm seasons, elongate down the slopes with time, only to fade away during colder seasons [16]. The process then repeats from year-to-year. Although they look like water seeps, a measurement of their terminal slopes shows values at the angle of repose for dry sand (Figure 6), suggesting that at least the terminal reaches of the RSL are dry granular flows and not liquid water flows [17].

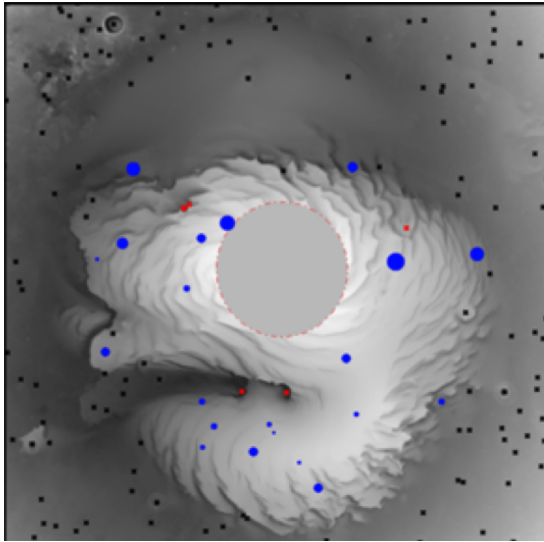


Figure 5. Apparent impact craters in the basal unit beneath the north polar ice cap. [10]

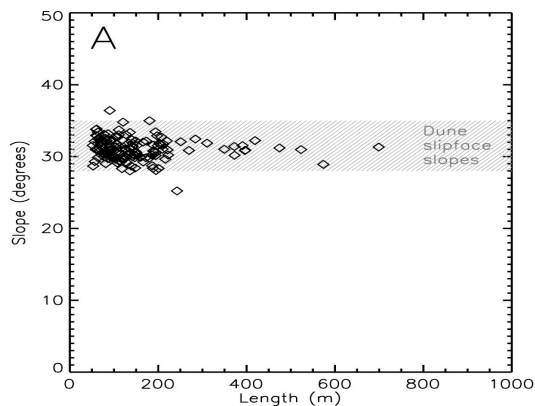
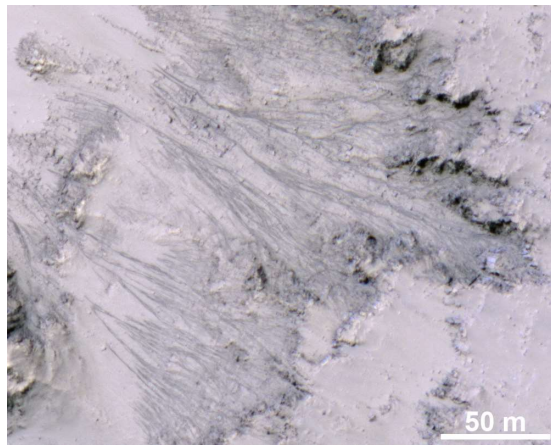


Figure 6. RSL in Palikir Crater (top, HiRISE image) terminate on slopes that match the angle of repose for dry sand (bottom), suggesting dry granular flows. [17]

The triggering mechanism for such a granular flow is unclear, and so the warm-season recurrence remains unexplained. Investigation of this phenomena by MRO continues.

At high latitudes CO₂ snow and frost in the autumn and winter seasons can form a transparent glaze ice layer that sublimates from below in the spring when sunlight again illuminates the polar latitudes [18]. Despite monitoring, MRO has been unable to observe the jetting action arising from volatilization of the CO₂, but it can observe the year-to-year evolution of the "spider-like" features produced by the sublimation jets (Figure 7) [19]. Movement and sublimation of blocks of CO₂ on sand dunes can also be characterized, and it is clear that CO₂ frost formation and subsequent sublimation can be a major agent in eroding the surface at higher latitude [20].

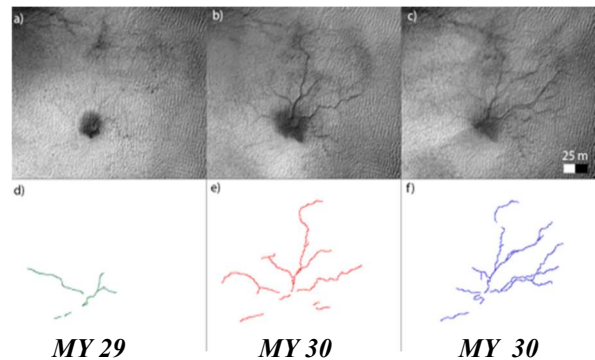


Figure 7. The evolving form of dust deposited by sublimating CO₂ is shown for two different Mars years (MY). The channels formed by CO₂ gas jets producing the "araneiform" features in the south polar "cryptic" terrain are delineated. [19]

2.4 Atmospheric & Polar Processes on Modern Mars

MRO MARCI and MCS directly measure atmospheric state fields and processes on interannual, seasonal, day-to-day and diurnally varying time scales. These are the predominant time-scales of variation in terms of atmospheric opacity (water and carbon dioxide ice clouds and dust hazes) and frequency of atmospheric storms. Adding the 6 full Mars years of MRO data taken by MARCI and MCS to the Mars Global Surveyor Wide-Angle Camera (WAC) and Thermal Emission Spectrometer (TES) respectively provides a decade of Mars years of daily global maps of the Mars atmosphere in the early afternoon and of atmospheric temperature and dust profiles both day and night.

Local dust storms occur in every season on Mars and can appear anywhere on the planet, but during southern spring and most of southern summer, local dust storms can expand to become regional events. In

rare years, a regional storm can grow or coalesce with other storms to produce a dust haze that encircles or even nearly covers most of the planet. The major dust-lifting activity is part of these local storms, but there may be several of these dust-raising centers which together produce a much more extensive dust haze. Collectively, these centers and the dust haze they produce are classified as a Planet-Encircling Dust Event (PEDE) [21].

Such events are the primary components of year-to-year variability in the modern Mars climate, and they can produce long-lasting, if ultimately ephemeral, surface effects. The redistribution of bright dust can mask some of the classical dark regions or raise their albedo in subsequent years and can perturb the seasonal cycles of carbon dioxide and perhaps water. Dust raised into the atmosphere is a powerful driver of the atmospheric circulation: The lofted dust absorbs sunlight and both absorbs and emits IR radiation. The radiative effects change temperature, which changes pressure, which changes winds. The changed circulation can further change atmospheric temperatures through adiabatic vertical motions, and horizontal winds can advect heat and dust, as well as raise more dust into the atmosphere [22].

MRO has previously reported [23] on a seemingly consistent progression of 3 regional events in a year without a planet-encircling event. Until this year, MRO had observed a PEDE only once, in 2007. That changed this year.

On June 1, one of the many local storms circumnavigating the north polar region in the jet stream there started down the Acidalia Storm track (red zone in Figure 8). As part of its programmatic duties, MRO MARCI alerted the team operating the solar-powered Opportunity Rover about the approaching storm. Most local dust storms continue to pass on by, obscuring the skies for a day or two before moving on, crossing the equator and into the southern subtropics, where they usually dissipate. This dust storm seemed to stall in the northern low latitudes, producing an expanding dust haze and triggering more dust activity off to the east. After a few more sols, local dust storms produced in the south polar jet stream (associated with the subliming seasonal cap) moved equatorward, with the dust hazes merging in the southern subtropics and then covering much of the eastern hemisphere. Finally, new dust-raising centers in Solis and Sinai Planum extended the dust haze to the west and the storm became a PEDE. A month after its onset, the PEDE had obscured most of the planet (Figure 9).

As of this writing, the PEDE is abating: MARCI data indicate most dust-raising centers have shut down, and MCS reports that temperatures in the middle atmosphere, which had increased substantially, were no longer rising and in some areas were decreasing. MARCI and ground-based observers report that the classical dark areas of Mars are beginning to reappear, suggesting that fall-out of the dust particles is outpacing the lofting of new dust.

Clearing of the atmosphere is likely to take many more weeks. By comparison with the 2001 PEDE, which occurred at approximately the same seasonal date, opacities which were $\tau > 5$ for many weeks over much of the planet would not fall below $\tau \sim 2$ until mid-September and would not reach unity until November. This event and the one in 2001 were the PEDEs with the earliest onset. That and the unusual stall of the current event in low latitudes are two notable attributes of this event. Data collection continues and analyses have begun in earnest; a key question is to understand the formative stages of this PEDE.

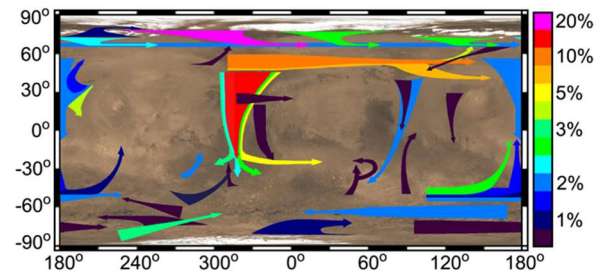


Figure 8. Local Dust Storm Pathways.
 Color indicates % of the total of local dust storms occurring on Mars in Mars Years 23-32 (1997-2015) moving in different tracks and zones. The global composite is based on MGS WAC and MRO MARCI daily global maps. [24]

2.5 Science Data Archiving

The MRO science investigation teams continue to deliver all standard and many special data products to the Planetary Data System within 3-9 months of data acquisition. The one exception to this was an interruption in delivery of some SHARAD data products for an extended period, but this is being addressed.

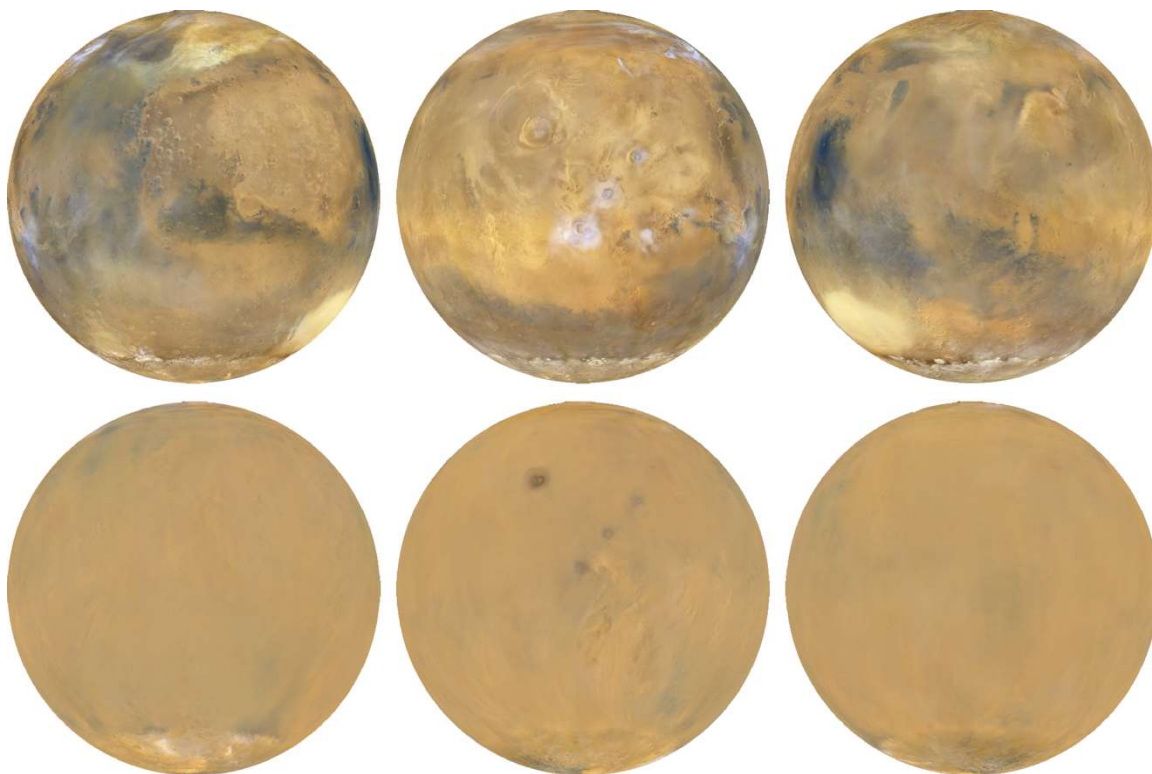


Figure 9. MARCI Observations of Mars before and during the 2018 PEDE
 MARCI daily global maps map-projected onto a sphere centered at 0° (left), 120°W (center), and 240°W (right) for May 28, 2018 (top row, centered at equator) and July 1 (bottom row, centered at 15°S, bringing the sunlit south pole into view). Daily global maps are mosaicked and interpolated from the 13 daily MARCI swaths generated by imaging cross-track limb-to-limb as MRO flies across Mars at a local time ~3 p.m. In the May 28 view, local storms move in the polar jet stream surrounding the condensing north polar cap; elsewhere the classical albedo features (e.g., Meridiani, top left, and Syrtis Major, top right) are clearly seen. On June 1 a local dust storm started moved into the Acidalia-Chryse basin (upper center of top left image) and eventually combined with new dust-raising centers to produce a nearly global dust haze (bottom panel) by the end of June. Note that the tops of Olympus Mons and the Tharsis volcanoes can still be identified.
 [Images courtesy of B. Cantor & M. Malin: *MRO MARCI / MSSS / JPL / NASA*]

3. Extended Mission Programmatic Support Functions

NASA has tasked the Mars Reconnaissance Orbiter Project to provide essential mission support to designated ongoing and future Mars missions. As shown in Table 1, every MRO payload element provides some measure of programmatic support. Current missions and campaigns being supported include MER-B, MSL, MAVEN, InSight, Mars 2020, ExoMars 2020, and the Human Exploration Zones.

3.1 UHF Relay

Relay involves sending commands to, and returning data from, landed spacecraft. This is accomplished via the Electra UHF transceiver. Relay data return represents less than 0.2% of the total data return by MRO, as it is limited by the performance of the UHF link, overflight durations, and occasionally multipath effects produced by surrounding terrain.

Table 1. Payload Element versus Programmatic Functions

Programmatic Function	HiRISE	CRISM	CTX	SHARAD	MCS	MARCI	Electra
Landing Site Reconnaissance	X	X	X	X			
Pre-EDL Atmospheric Study					X	X	
EDL (Critical Event Coverage)	X		X				X
Post-EDL Assessment	X		X		X		X
Traverse/Operations Support	X	X	X		X	X	
Relay (Active): MER-B, MSL							X
Relay (Future): InSight, Mars 2020, ExoMars 2020							X

Campaigns/Mission Supported:

Phoenix* MER-A* MER-B MSL MAVEN InSight
 Red Dragon* ExoMars EDM* Mars 2020 ExoMars 2020 Human Exploration Zones (EZs)

*Mission Support Completed

Spacecraft assembly and test revealed that several of the MRO science instruments did not meet radiated emission requirements in the UHF band in which the Electra radio operates. The EMI from those instruments significantly degrade Electra's UHF receiver performance. To mitigate this impact, MRO has developed a special relay mode of operations dubbed the "relay quiet mode." In relay quiet mode (RQM), certain instruments have their operations curtailed: CRISM is not allowed to observe or gimbal, SHARAD is not allowed to transmit, and MCS is put into a standby mode with its apertures oriented to minimize EMI. HiRISE has no detectable EMI, while MARCI and CTX have minor levels, so those instruments are permitted to operate normally during relay passes.

In EM4 MRO regularly relays with the Mars Science Laboratory (MSL) rover *Curiosity* and the Mars Exploration Rover (MER-B) *Opportunity*. MRO is considered the prime relay link for *Curiosity* and typically provides 14 relay passes per week, returning an average of 225 Mbits of data per pass using an adaptive data rate (ADR) scheme. To ensure support of the MER-B rover in the event the *Odyssey* orbiter is not available, MRO provides *Opportunity* ~2-3 relay passes per week, returning an average of 50 Mbits of data per pass using a fixed data rate scheme. Table 2 summarizes MRO relay support for all missions.

3.2 Preparations for InSight EDL and Surface Relay

As for past missions [25], MRO will provide critical event coverage of the InSight Entry, Descent, and Landing. Critical event coverage consists primarily of an open loop (OL) recording of the radio signal from InSight. This requires the MRO vehicle to be positioned in such a way that the InSight lander

during descent is within the field of view (FOV) of the Electra antenna on the MRO nadir deck.

Table 2. MRO Relay Data Volume
(as of July 31, 2018)

Lander	Total Passes	Average Volume/Pass	Total Return Volume
PHX	240	39.4 Mbits	9.4 Gbits
MER-A	24	45.6 Mbits	1.1 Gbits
MER-B	422	46.0 Mbits	19.4 Gbits
MSL	3937	224.9 Mbits*	865.4 Gbits
EDM	5**	0 Mbits	0 Gbits
Total	4628	---	895.3 Gbits

* Nominal ADR passes

** Due to EDM failure, relay links with the lander on the surface were never established. MRO imaging of the landed EDM hardware supported the ExoMars investigation

To properly position MRO for InSight EDL, the orbit plane as well as the orbit in-track (or downtrack) position must be controlled. The orbit plane is represented by the LMST of the MRO orbit ascending node. The downtrack position is represented as a latitude crossing time. For EDL, the InSight Mission/Navigation Team has asked MRO to position itself at 2:52:00 pm LMST at the time it crosses 19.6°S latitude on November 26, 2018. MRO will achieve these conditions using a sequence of three maneuvers with the option for a fourth contingency maneuver. The maneuver plan for InSight EDL is summarized in Table 3. It should be noted that OCM-1 was executed last year (2017) and present predictions have MRO at 2:50:42 pm on November 26, well within required tolerances.

Table 3. Maneuver Plan for InSight EDL

Maneuver	Date	ΔV (m/s)	Purpose
OCM-1	3/4/17	2.43	LMST
OSM-1	8/22/18	0.32	Downtrack
OSM-2	10/17/18	0.31	Downtrack
OSM-3	11/14/18	---	Contingency

OCM (Orbit Correction Maneuver) – Inclination Control
 OSM (Orbit Synchronization Maneuver) – Downtrack Control

The open loop recording will start just prior to entry interface and continue until five minutes after InSight touchdown. To enhance the quality of the UHF link between MRO and InSight during EDL, MRO will power off instruments that are known to degrade the UHF link: CRISM, SHARAD, MCS, and MARCI. During the EDL descent phase, the Electra antenna must be pointed at InSight and maintained within 30 deg of the Electra antenna boresight. This is accomplished using a slow attitude slew. Once the open loop recording completes and it is returned to Earth, spacecraft engineers can demodulate the recording and determine key characteristics of InSight's EDL profile.

As MRO did with Phoenix and MSL, HiRISE will attempt to image InSight while on its parachute. The range, atmospheric dust opacity, and image geometry for this particular EDL event is more challenging than previous missions so an image is not guaranteed.

Once InSight is on the surface, MRO will provide InSight UHF surface relay capability with a heightened level of support to troubleshoot anomalies for the first 12 Sols. The first MRO overflight of the InSight landing site will occur 12 hours after touchdown. Because of the limited capabilities of the InSight UHF transceiver, InSight will communicate with MRO using only fixed data rates.

Using its imaging capabilities, MRO plans to image the InSight landing site post-EDL. Only three InSight overflights in the first 12 Sols will satisfy the imaging lighting (daylight) and spacecraft roll constraints and all three will be scheduled for CTX

(with its 20 km wide field-of-view) and HiRISE imaging (with its better resolution but narrower swath). The first imaging opportunity will target the nominal InSight landing location unless a landing location update is received from the InSight Project. The second and third will be retargeted based on the results acquired from the first imaging. The timeline for the first 12 Sols of MRO support for InSight is shown in Figure 10. The timeline shows science instrument off/on periods and overflight periods at low elevation angle.

The proximity of *InSight's* Elysium Planitia landing site and *Curiosity's* Gale Crater location creates a contention for relay services that impact both missions. With a separation distance of only 500 km, MRO will overfly both of these surface vehicles in a matter of minutes. Rather than being restricted to support one mission or the other, MRO has developed a “split-pass relay” capability that allows for non-overlapping, reduced volume UHF communications to both vehicles on the same overflight. During the last quarter of 2016, new split-pass relay blocks completed their development and underwent rigorous ground testing. They were uplinked to the spacecraft as part of a relay block library update in December 2016. In June 2018, MRO successfully demonstrated full readiness of its split-pass capability using the *Curiosity* rover as a relay partner. Relay passes with Curiosity as the first and then as the second vehicle in the split-pass executed perfectly with proper Electra set-up, hail durations, and data volume returned.

3.3 Landing Site Reconnaissance

Landing site reconnaissance includes the identification, characterization, and certification of potential landing sites for future landed missions. MRO uses a priority and allocation scheme in its scheduling of relay and targeted observations. Relay receives first priority in the scheduling process. Programmatic landing site observations typically have

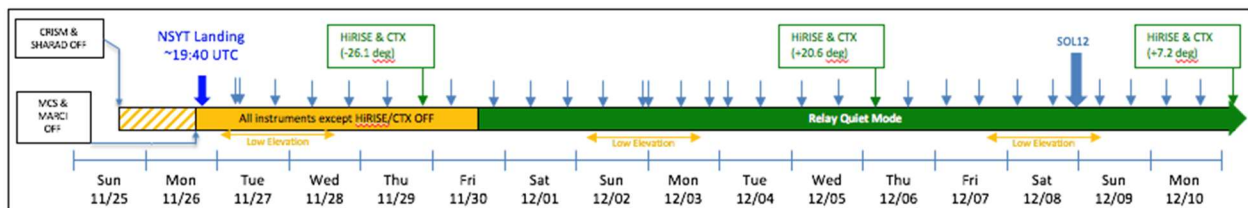


Figure 10. Timeline of MRO Support for InSight EDL and Early Surface Operation
 Down arrows indicate the planned InSight relay passes; green rectangles indicate imaging opportunities.

a high priority but are limited in number during each planning cycle.

As noted in reference [26], MRO completed its site reconnaissance of candidate sites in Elysium Planitia for the 2018 InSight Mission. MRO is currently focusing on reconnaissance data sets for the NASA Mars 2020 mission and the ESA ExoMars 2020 mission. Figure 11 shows HiRISE coverage of the final Mars 2020 landing sites and the downselect to the three remaining candidates: Jezero Crater, NE Syrtis, and Columbia Hills. In addition to the 2020 missions,

MRO supports several future landing site campaigns, including future Human Exploration Zones (EZ) and some areas that are not yet assigned to any specific mission. Figure 12 shows the landing locations of MER-B and MSL as well as candidate NASA and ESA landings sites for their respective 2020 missions. Further discussion on MRO's landing site reconnaissance capabilities and methods can be found in reference [27].

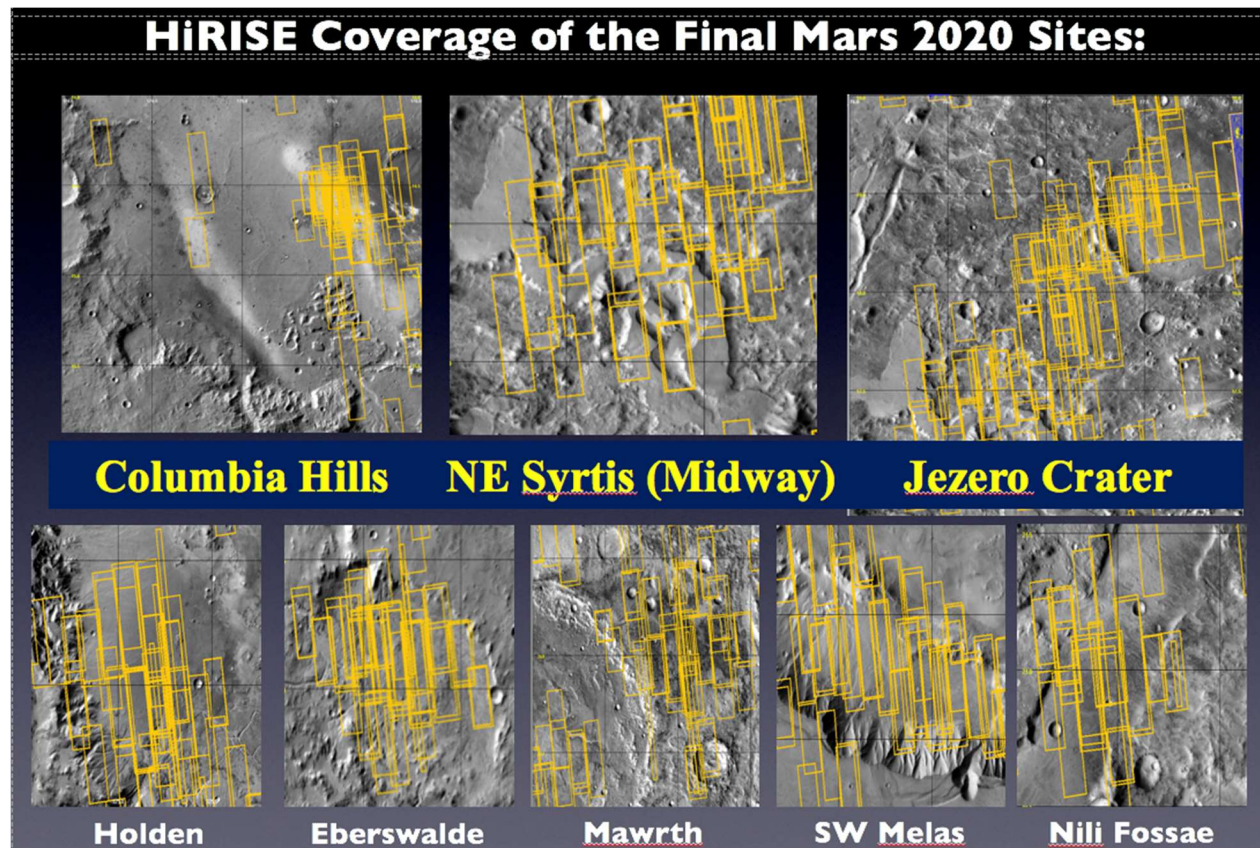


Figure 11. HiRISE Coverage of the Final Mars 2020 Candidate Landing Sites
 [MRO HiRISE / U. Arizona / JPL / NASA]

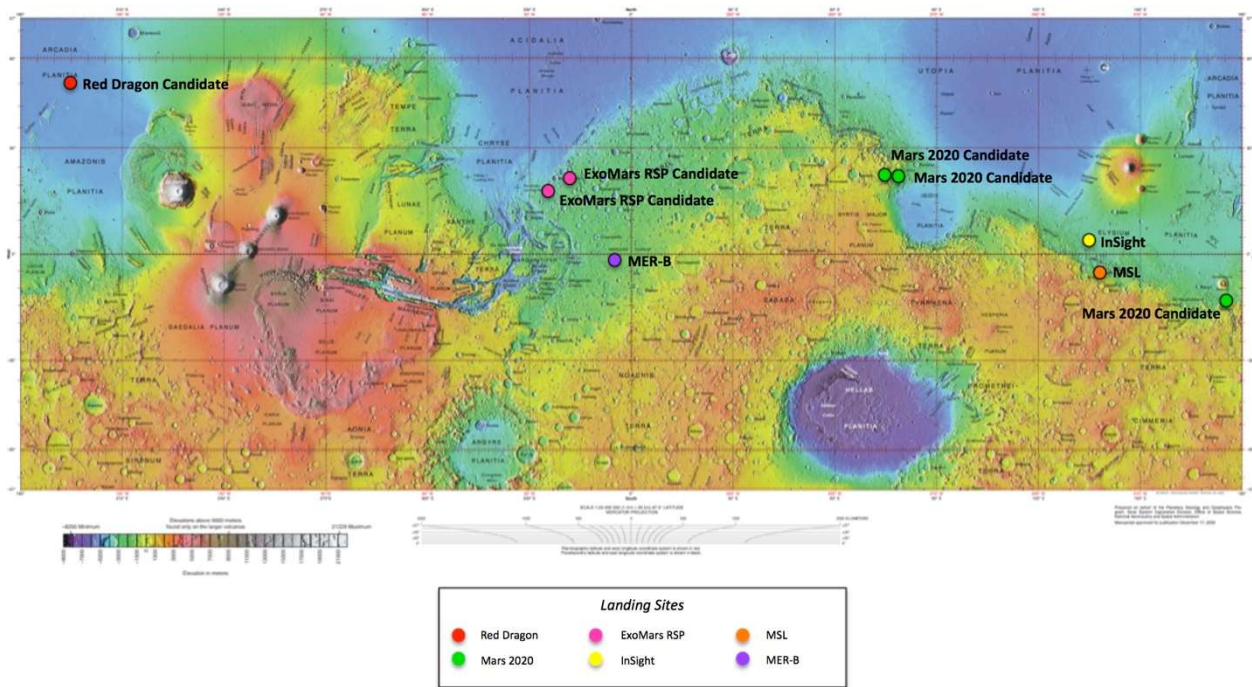


Figure 12. Current and Candidate Landing Sites

3.4 Environmental Data to support Surface Operations and Mission Design

MCS and MARCI provide atmospheric structure and change characterization, including data for model validation to assist design and simulation of flight performance. These data are a significant aid to EDL planners. As described in Section 2.4, MARCI and MCS provide weather updates during periods of significant dust events, of special interest for critical events like EDL and for surface operations of solar-powered craft. In addition to atmospheric support, HiRISE, CTX, and CRISM data aid the traverse planning of *Curiosity* and *Opportunity* by identifying targets of high scientific interest, safe paths of travel (Figure 13) and areas of dangerous terrain.

4. Flight and Mission Operations Challenges

Now entering its 12th year of orbital flight, the MRO vehicle remains fully capable of carrying out an ambitious mission plan in support of the Mars Exploration Program. The spacecraft and payload is fully operational within all required performance regimes with the exception of CRISM which can no longer perform IR observations. Robust margins have enabled mitigation of the normal aging effects on both spacecraft and payload.

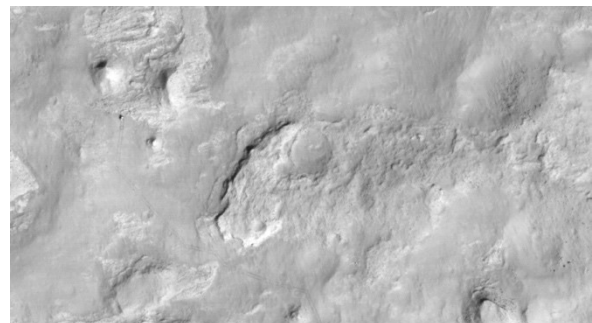


Figure 13: Curiosity rover leaves its tracks across the floor of Gale Crater on the way to the slopes of Mt. Sharp.

In-flight anomalies and known risks [28] do not immediately threaten operation of the orbiter for further science observations or for support of current and future landed missions.

4.1 Inertial Measurement Units – All-Stellar Attitude Determination

In 2013, the Laser Intensity Monitor (LIM) current for the Y-axis of the IMU-1 began to decline in a manner consistent with ~4-5 months of use remaining before reaching an end-of-life condition. In order to maintain IMU redundancy for safe mode operations, a

swap to IMU-2 was commanded in August 2013. IMU-2 has been performing nominally, with a LIM profile consistent with normal operating conditions.

It is expected that IMU-2 will continue to be operational for its 10-year design lifetime, and MRO will be able to support the prime surface mission of the Mars 2020 rover in 2021-2024. However, loss of both IMUs would result in the end of mission as an IMU is necessary for safe mode operation. As a contingency measure, the Project has developed an All-Stellar (AS) attitude determination mode that uses the orbiter's star trackers, allowing nominal spacecraft operations to continue without the IMUs powered.

On April 19, 2017, the all-stellar capability was installed on-board the spacecraft as a patch to the existing flight software code base. To assess the performance of the all-stellar algorithm, eight flight demonstrations were performed in the period from April 2017 to January 2018. Each flight demonstration expanded the AS operational envelope until finally the last demonstration tested full capability. In the last demonstration (performed in January 2018) the IMUs were powered off and AS was allowed to operate in control of the vehicle for four days.

In March 2018, the all-stellar flight demonstration activities were formally assessed in two reviews: a detailed attitude control review and a spacecraft/mission system review. The ACS review concluded that the AS algorithm had been implemented correctly and that it met all of its performance requirements. The system-level review concluded that the spacecraft, science payload, and ground systems were all ready for nominal and contingency all-stellar operations.

On March 19, 2018, the project transitioned to nominal all-stellar operations powering off both IMUs. All-stellar remained prime for spacecraft attitude determination until an extended star tracker outage period transitioned the vehicle back to gyro control on June 29th. The outage period was determined to be caused by sparse sky conditions. After resetting star tracker parameters, the vehicle was commanded back to all-stellar attitude determination mode on July 2nd. The next planned usage of MRO's IMU-2 will be on August 22nd for OSM-1.

4.2 Spacecraft Power Management

Due to its low altitude, the MRO spacecraft experiences ~35 minutes of solar eclipse every orbit. Two nickel hydrogen batteries provide power for the spacecraft during the eclipse periods. Since the start of orbital operations, the batteries have experienced steadily decreasing End of Discharge (EOD) voltages. The EOD voltage is reached at the end of each eclipse period, when the batteries are at their lowest state of

charge for the orbit. This decrease is as expected for the design of the batteries and the orbital environment, and while overall performance has been better than originally predicted, the batteries have been steadily losing capacity, while internal impedances have been growing. Eventually the batteries will reach a point ("knee") in their voltage curves at which the voltage will drop off rapidly and the spacecraft will experience an under-voltage fault condition. For this reason, battery operations are designed to maintain an EOD voltage consistent with spacecraft power needs throughout the Mars year. Using the current spacecraft battery loading scheme (full science and relay payload operations), the batteries could have reached their EOD voltage limits in 2019. To prevent this from happening, the MRO Project has developed a phased battery management and conservation plan.

The first phase of this plan was to shift the heater loads of select spacecraft components into sunlight, thereby reducing battery discharge during eclipse. To prevent these components from becoming too cold during eclipse, they are pre-heated during the sunlit portion of the orbit. This first phase was implemented in early 2017 through sequencing and then later by a new spacecraft eclipse block.

The second phase of the battery management plan called for shifting payload (instrument) loads to sunlight. The primary action associated with the second phase was the shifting of HiRISE warm-up images out of eclipse. This was implemented in April 2017. As another means of reducing instrument power loads, Ball Aerospace was asked to investigate HiRISE heater setpoint changes. In April 2018, Ball Aerospace developed a new set of HiRISE heater setpoints that would provide additional power savings to the spacecraft (~18 W per orbit). This is currently planned to be implemented in early 2019. Given the sensitivity of the HiRISE instrument to thermal change, a special recalibration activity will have to accompany the setpoint adjustments. If the two phases described above are not sufficient, a third phase of the plan would require MRO to shift its orbital node to later local mean solar times which have shorter eclipse durations. This option is extremely undesirable for MRO science because it will have a significant impact on instrument signal-to-noise (SNR).

In September 2017, MRO experienced a low voltage safing of the science payload. Subsequent investigation revealed a much lower battery capacity than expected, resulting in an unexpectedly low bus voltage toward the end of eclipse. This was the first time the batteries had been in such a low voltage condition since spacecraft assembly and test. Potential causes/contributing factors for this event include: battery degradation higher than expected, voltage "knee" increases due to lower battery temperatures,

and operationally charging batteries to a level below full capacity. To combat these effects, the MRO Spacecraft Team has begun a campaign to recharge the batteries to a higher state of charge. Over time, this will increase the available discharge capacity of the batteries and improve the health of the battery cells. There are currently no indications of battery health issues and once reconditioned by charging the batteries to near their exothermic state, the batteries are expected to be viable for many years to come.

4.3 Payload Capabilities

The ability of CRISM cyro-cooler 3 to keep the IR detector at cold enough temperatures for useful SNR gradually degraded in 2017 to the point that it was no longer practical to attempt observing with the IR spectrometer. After a promising start, attempts to restart CRISM cooler 1, which had been side-lined due to earlier erratic behavior, ended with the cooler showing the same signs of failure that had ended cooler 2's utility. The coolers, all of which had far out-lived expectations, had enabled acquisition of an extraordinarily rich data set, which has already yielded many discoveries, but which will continue to be mined for years to come. With the loss of the IR spectrometer and with concerns about battery management and IMU use, it was also decided to forgo the special CRISM limb scans that had helped to characterize atmospheric phenomena. In the meantime, the VNIR spectrometer continues to operate nominally.

After the seventh AS flight demonstration in October 2017, the HiRISE Science Team identified a blurring effect in their highest resolution imaging. (Blurring has been attributed to about ~40% of the highest resolution images acquired during a several month period). Originally thought to be associated with the all-stellar controller parameters, further investigation by HiRISE identified this blurring to have started in early 2017, prior to the loading of the all-stellar patch. An intense investigation by the Project ensued.

It was noted that the number of blurred images had decreased after passing aphelion in October 2017. In January-February 2018, the HiRISE Science Team and Ball Aerospace re-examined HiRISE thermal data and found that temperature changes in the secondary mirror structure, in conjunction with a colder environment during aphelion, was causing the camera to lose focus.

As part of the battery mitigation activities, HiRISE no longer took warm-up images during eclipse. These warm-ups were meant to mitigate bit-flip errors that have increased over time, likely due to the effects of chlorine contamination in the detectors. However, the deletion of warm-up images in eclipse was letting the secondary structure get cold enough that it affected the

focus. To remedy the focus issues, HiRISE is planning on re-enabling their optical heaters during imaging. This will require a patch to the HiRISE flight software to remove the automatic disabling of the thermal control process during all image sequences. The patch is currently expected to be installed in HiRISE in August 2018.

The Mars Climate Sounder continues to work around occasional position errors in the instrument actuators. Azimuth movement, needed to do cross-track scanning to record local time variations, to intercompare with other missions, and to minimize relay interference, is a bit more problematic than the standard in-track elevation scanning. The effect thus far has been to lose an occasional few days of observation. There are no other instrument concerns.

MARCI, CTX, and SHARAD have reported no anomalies or concerns and are expected to continue as in the past.

5. Summary

In 2017 and 2018, the project team focused considerable time on actions to extend spacecraft life. The all-stellar attitude determination mode is now prime for operations. Spacecraft power management and battery reconditioning are improving the state of the spacecraft batteries. Concerns over HiRISE image blurring have been traced to changes in the thermal operation of the instrument and methods to mitigate this problem have been developed. As the investigation into the HiRISE blur showed, MRO is a complex vehicle with subtle subsystem interactions.

As of July 2018, most MRO preparations for the arrival of the InSight lander have been completed. New relay capability has been demonstrated and MRO is maneuvering to its target point for InSight EDL. The final development of the EDL sequence that will record the radio signal and attempt to image InSight has completed preliminary design and is in test.

In parallel with the activities described above, MRO has continued to carry out its EM4 science and programmatic objectives. MRO's powerful suite of science instruments continues to unveil Mars in unprecedented detail. Remarkably, most MRO instruments have retained their essential capabilities, even as they are now in their 12th year of operation in Mars orbit. The MRO science investigations have shown that Mars is a diverse planet with a complex geologic history. In particular, the diversity of early water-rich environments shows preservation potential for signatures of ancient life, if it ever developed. Furthermore, the longevity of the mission and the higher spatial resolutions of its instruments, whether viewing the surface, atmosphere or subsurface have

revealed a planet where the processes of change are still at work.

Notable science metrics (as of July 27, 2018) include:

- Over 333 Terabits of Science Data returned
- Acquisition of over 280,000 targeted images, and image equivalents:
 - CTX: 99.6% of the planet imaged at 6 m/pixel;
 - CRISM (planet coverage at low-opacity)
 - ~86% in 72 channel VIS & NIR @200 m/pixel;
 - ~39% in 256 VIS/NIR channels @200 m/pixel;
 - ~86% in hyperspectral VIS @ 200 m/pixel;
 - ~83% hyperspectral VIS @ 100 m/pixel;
 - HiRISE (equivalent area coverage):
 - ~ 3 %, >56,000 images, most at 0.3 m/pixel;
 - ~0.4% of Mars covered in stereo (~5600 pairs);
 - MARCI: Daily Global Maps mosaicked from 13 swaths per day for ~6.3 Mars years (54,254 images);
 - MCS: Atmospheric Profiling on 13 orbits per day for ~6.3 Mars years (168.8 million soundings of temperature, dust, water ice);
 - SHARAD: Shallow Subsurface Soundings (~10 m to 1500 m depending on composition) covering half the planet (~23,000 observing strips).

The Mars Reconnaissance Orbiter has entered its 13th year of flight. No other spacecraft, currently flying or in development, has the scientific and programmatic capabilities of MRO. Due to this dual-mode nature, the MRO spacecraft has become the workhorse of the Mars Exploration Program. As part of a new 3-year NASA Planetary Mission Senior Review cycle, MRO will propose next spring to continue pursuit of compelling science even as it carries out its extensive programmatic duties. With large fuel reserves (199 kg) and significant subsystem life remaining, MRO is expected to stay on station in its low altitude orbit in support of the Mars Exploration Program until the end of the 2020's.

Acknowledgements

The authors wish to acknowledge the MRO Science Teams (and their leads): the CTX/MARCI Team at Malin Space Science Systems (Michael Malin); the HiRISE Team at the University of Arizona (Alfred McEwen); the CRISM Team at John Hopkins University Applied Physics Lab (Scott Murchie); the MCS Team at JPL (John T. Schofield), the Joint ASI/US SHARAD Team (TL: Roberto Seu; DTL: Nathaniel Putzig) and the Gravity Science Team (TL: Maria Zuber). And special thanks go to the Flight Team personnel at Lockheed Martin Space Systems

and JPL, without whom the observations contained herein and this paper would have not been impossible.

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

- [1] M.D. Johnston, R.W. Zurek, The Mars Reconnaissance Orbiter Mission: Continuing a Record of Exploration from Mars Orbit, IAC-17-A3.3A.7, 68th International Astronautical Congress, Adelaide, Australia, 2017, 25-29 September.
- [2] M.D. Johnston, J.E. Graf, R.W. Zurek, H. J. Eisen, B. Jai, "The Mars Reconnaissance Orbiter Mission: From Launch to the Primary Science Orbit," 2007 IEEE Aerospace Conference, IEEEAC Paper #1237, March 2007.
- [3] M.D. Johnston, D.E. Herman, R.W. Zurek, C. Edwards, "Mars Reconnaissance Orbiter Mission: Extended Dual-Purpose Mission," 2011 IEEE Aerospace Conference, IEEEAC Paper #1278, March 2011.
- [4] R.W. Zurek, S.E. Smrekar, An Overview of the Mars Reconnaissance Orbiter (MRO) Science Mission, *J. Geophys. Res.*, 112, E05S01, doi:10.1029/2006JE002701, 2007.
- [5] B.L. Ehlmann, C.S. Edwards (2014), Mineralogy of the Martian Surface, *Ann. Rev. Earth Plan. Sci.* 42, 291-315, doi:10.1146/annurev-earth-060313-055024.
- [6] C. E. Viviano-Beck, et al., Fresh craters as compositional probes for dust-covered bedrock in Tharsis and Elysium, Mars. Lunar and Planetary Science Conference, 2017.
- [7] R.J. Phillips, et al. (2011), Massive CO₂ ice deposits sequestered in the south polar layered deposits of Mars, *Science* 332, 838-841, doi:10.1126/science.1203091.
- [8] J.J. Plaut, et al. (2009), Radar evidence for ice in lobate debris aprons in the mid-northern latitudes of Mars, *Geo. Phys. Res. Lett.* 36, L02203, doi:10.1029/2008GL036379. Holt, J.W., et al. (2008), Radar sounding evidence for buried glaciers in the southern mid-latitudes of Mars, *Science* 322(5905), 1235-1238, doi:10.1126/science.1164246.
- [9] F.J. Foss II, et al. (2017), 3-D imaging of Mars' polar ice caps using orbital radar data, *The Leading Edge*.
- [10] N.E. Putzig et al (2017), Three-dimensional radar imaging of structures and craters in the Martian polar caps, *Icarus*. DOI: 10.1016/j.icarus.2017.09.023.

- [11] C.J. Bierson, et al. (2016), Stratigraphy and Evolution of the buried CO₂ deposit in the Martian south polar cap, *Geophys. Res. Lett.*, *43*, 4077-4080, doi:10.1002/grl.53443.
- [12] C.M. Dundas, et al. (2014), HiRISE observations of new impact craters exposing Martian ground ice, *J. Geophys. Res. Planets*, *119*, 109-127, doi:10.1002/2013JE004482.
- [13] A.M. Bramson, et al. (2015), Widespread excess ice in Arcadia Planitia, Mars, *Geophys. Res. Lett.* *42*(16), 6566-6574, doi:10.1002/2015GL064844.
- [14] C.M. Stuurman, et al. (2016), SHARAD detection and characterization of subsurface water ice deposits in Utopia Planitia, Mars, *Geophys. Res. Lett.*, *43*, doi:10.1002/2016GL070138.
- [15] B. A. Campbell and G. A. Morgan (2018), Fine-scale layering of Mars polar deposits and signatures of ice content in nonpolar material from multi-band SHARAD data processing, *Geophys. Res. Lett.*, doi: 10.1002/2017GL075844.
- [16] A. S. McEwen et al. (2011), Seasonal flows on warm Martian slopes. *Science*, *333*, 740-743.
- [17] C. M. Dundas et al. (2017), Granular flows at recurring slope lineae on Mars indicate a limited role for liquid water. *Nature Geoscience* *10*, 903-907.
- [18] H.H. Kieffer, et al. (2006), CO₂ jets formed by sublimation beneath translucent slab ice in Mars' seasonal south polar ice cap. *Nature*, *442*, 793-796, doi:10.1038/nature04945.
- [19] C.J. Hansen, et al. (2010), HiRISE observations of gas sublimation-driven activity in Mars' southern polar regions: I. Erosion of the surface. *Icarus*, *205*(1), 283-295, doi:10.1016/j.icarus.2009.07.021.
- [20] G. Portyankina, et al. (2017), Present-day erosion of Martian polar terrain by the seasonal CO₂ jets, *Icarus*, *282*, 93-103, doi:10.1016/j.icarus.2016.09.00.
- [21] B.A. Cantor (2007), MOC observations of the 2001 Mars planet-encircling dust storm, *Icarus*, *186*, 60-96.
- [22] R. W. Zurek et al. (1992), Dynamics of the atmosphere of Mars. *Mars*, ed. H. Kieffer et al., U. Ariz. Press, Tucson, 835-933.
- [23] D.M. Kass, et al. (2016), Interannual similarity in the Martian atmosphere during the dust storm season, *Geophys. Res. Lett.* *43*, doi:10.1002/2016GL068978.
- [24] B. A. Cantor, M. C. Malin and K. E. Edgett (2014), "Martian Dust storms – Observations by MGS-MOC and MRO-MARCI", 8th *International Conference on Mars*, LPI Contribution 1791, p. 1316.
- [25] S.V. Wagner, P.R. Menon, and S.W. Demcak, "Mars Reconnaissance Orbiter: Ten years of Maneuver Support for Science Operations and Entry, Descent, and Landing Sequences," AAS/AIAA Space Flight Mechanics Meeting, AAS 17-287, San Antonio, TX, February 5-9, 2017.
- [26] M. A. Golombek et al. (2017), Selection of the InSight landing site, *Space Sci. Rev.*, *211*:5-95, DOI 10.1007/s11214-016-0321-9.
- [27] M. Brennan, M.D. Johnston, "Mars Reconnaissance Orbiter Landing Site Reconnaissance Capability," 2017 IEEE Aerospace Conference, doi:10.1109/AERO.2017.7943578, March 2017.
- [28] T. J. Bayer, "In-Flight Anomalies and Lessons Learned from the Mars Reconnaissance Orbiter Mission – an Update", 2009 IEEE Aerospace Conference, IEEEAC Paper #1086, March 2009.